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A critical review on energy use and savings in the cement industries

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ABSTRACT

The cement sub-sector consumes approximately 12–15% of total industrial energy use. Therefore, a state of art review on the energy use and savings is necessary to identify energy wastage so that necessary measures could be implemented to reduce energy consumption in this sub-sector. In this paper energy use at different sections of cement industries, specific energy consumption, types of energy use, details of cement manufacturing processes, various energy savings measures were reviewed and presented. Various energy savings measures were critically analyzed considering amount of energy that can be saved along with the implementation cost. Amount of CO_2 reduction has been presented along with the payback period for different energy savings measures as well.

This study complied a comprehensive literature on the cement industries in terms of Thesis (MS and PhD), peer reviewed journals papers, conference proceedings, books, reports, websites. It has been observed that China producing major share of global cement production. Coal contribute major share of fuel used in cement industries. However, along with conventional fuels, industries are moving towards the use of alternative fuels to reduce environmental pollution. It was reported that cement industries are moving from wet process to dry process as it consume less energy compared to wet process.

Contents

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1. Introduction

Industrial sector energy consumption varies from 30% to 70% of total energy used in some selected countries as reported in the literatures [1–9]. A sizeable amount of energy is used in manufacturing cement. Therefore focus should be given on the reduction of energy and energy related environmental emissions locally and globally [10–14]. It was reported that this segment of industry consumed about 12% of total energy in Malaysia [15] and 15% of total consumption in Iran [15,16].

Being an energy intensive industry, typically this segment of industry accounts for 50–60% of the total production costs [17]. Thermal energy accounts for about 20–25% of the cement production cost [18]. The typical electrical energy consumption of a modern cement plant is about 110–120 kWh per tonne of cement [19]. The main thermal energy is used during the burning process, while electrical energy is used for cement grinding [20]. Fig. 1 shows electrical and thermal energy flow in a cement manufacturing process.

World demand for cement was 2283 million tonnes in 2005 and China accounted for about 47% of the total demand. It is predicted that the demand will be about 2836 MT in the year 2010. China will increase its demand by 250 million tonnes during this period. This increase will be higher than the total annual demand for European Union [22]. It was reported that Japan and the US, India is the fourth largest cement-producing country in the world. Mandal and Madheswaran [23] reported that production of cement increased from 2.95 million tonnes in 1950–1951 to 161.66 million tonnes in 2006–2007 in India. Table 1 shows the annual production of cement for few selected countries around the world. Table 2 shows the anticipated demand for cement in different continents along with the growth rate up to the year 2010.

Specific energy consumption in cement production varies from technology to technology. The dry process uses more electrical but much less thermal energy than the wet process. In industrialized countries, primary energy consumption in a typical cement plant is up to 75% fossil fuel and up to 25% electrical energy using a dry process. Pyro-processing requires the major share of the total thermal energy use. This accounts for about 93–99% of total fuel consumption [20,25,26]. However, electric energy is mainly used to operate both raw materials (33%) and clinker crushing and grinding (38%) equipment. Electrical energy is required to run the auxiliary equipment such as kiln motors, combustion air blowers and fuel supply, etc. (22%) to sustain the pyro-process. Fig. 2 shows the electrical energy consumption per tonne of cement production for selected countries around the world. About 94% of the thermal energy requirement is met by coal in the Indian cement manufacturing and the remaining part is met by fuel oil and high speed diesel oil. Natural gas is not sufficiently available for the cement industry in India [27]. The final energy mix of an industry is dominated by coal and oil as presented in Tables 3, 5 and 6.

About 29% of the expense is spent on energy, 27% on raw materials, 32% on labor and 12% on depreciation in a cement industry. Therefore, cement industry is characterised by intensive industry throughout its production stages and the calcination of its raw

Table 1
Global cement production statistics for the year 2005 [24].

Sectors	Production (MT/yr)	Share (%)
China	1064	46.60
India	130	5.70
United states	99	4.30
Japan	66	2.90
Korea	50	2.20
Spain	48	2.10
Russia	45	2.00
Thailand	40	1.80
Brazil	39	1.70
Italy	38	1.70
Turkey	38	1.70
Indonesia	37	1.60
Mexico	36	1.60
Germany	32	1.40
Iran	32	1.40
Egypt	27	1.20
Vietnam	27	1.20
Saudi Arabia	24	1.10
France	20	0.90
Other	392	17.20
World	2284	100

Table 2
Demand for cement (million tonnes) for different continents [22].

Demand for cement	2005	2010	Growth rate (%)
North America	179	200	2.9
Western Europe	208	236	2.2
Asia/Pacific	1500	1900	5.2
Other regions	405	500	4.7
World cement demand	2283	2836	4.7

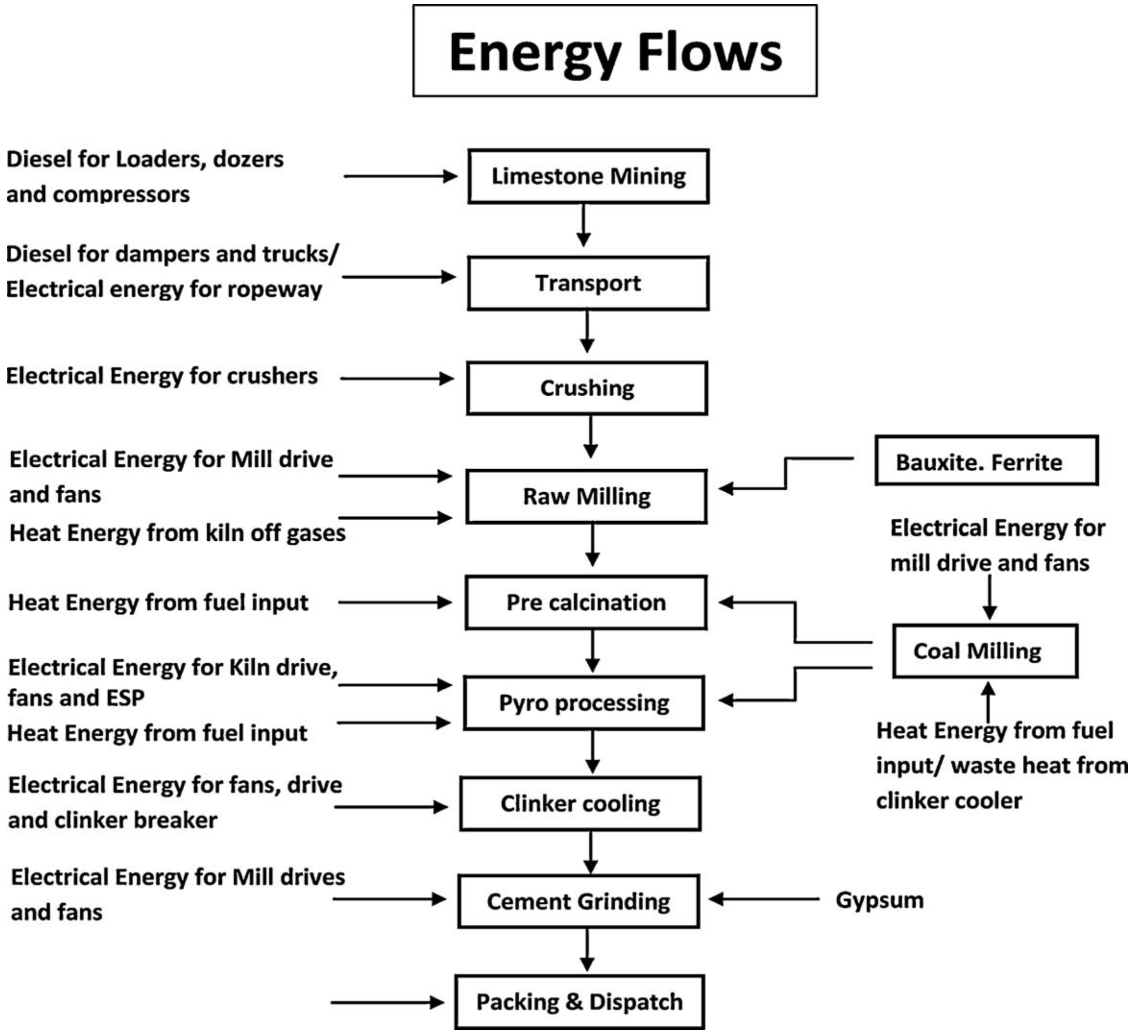

Fig. 1. Electrical and thermal energy flow in a cement production process [21].

materials. Consequently significant amounts of greenhouse gases (GHG) emissions are released to the atmosphere due to burning of fossil fuel to supply energy need for cement industries [11]. Specific thermal energy consumption in cement industries is found to be about 4 and 5 GJ/tonne [28].

As this segment of industries consume about 12–15% of total energy consumption, necessary measures are to be taken to reduce energy use along with the prevention of environmental degradation due to the release of carbon dioxide to the atmosphere.

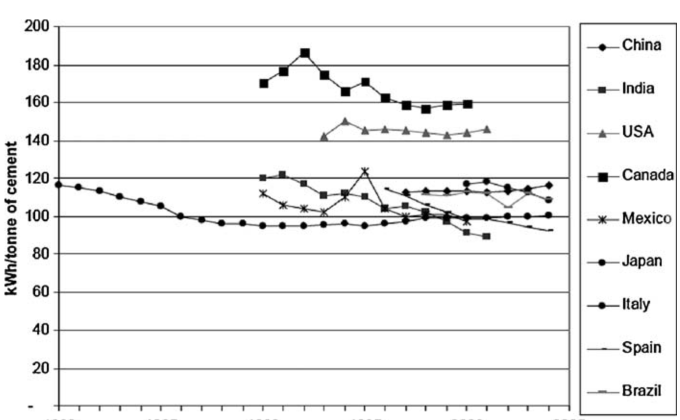

Fig. 2. Electricity consumption per tonne of cement for few selected countries. *Source*: Ref. [24].

In the literature, there are review works on the electrical motor and compressed air energy use and savings by [4,5]. Ziya et al. [29] also reported a review work on industrial energy savings strategies. To the best of authors knowledge, there is no comprehensive review on the energy use, savings, SEC for the cement industries. It is expected that this review will fill that gap and this study will be useful for global policy makers, researchers, and industrial energy users. Moreover, this study will create a strong awareness about energy savings in cement industries.

Table 3
Electrical energy distributions in a cement industry [21].

Section/Equipment	Electrical energy consumption (kWh/tonne)	Share (%)
Mines, crusher and stacking	1.50	2.00
Re-claimer, raw meal grinding and transport	18.00	24.00
Kiln feed, kiln and cooler	22.00	29.30
Coal mill	5.00	6.70
Cement grinding and transport	23.00	30.70
Packing	1.50	2.00
Lighting, pumps and services	4.00	5.30
Total	75.00	100.00

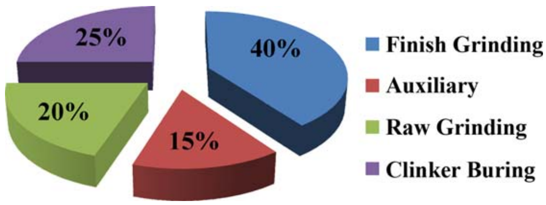

Fig. 3. Energy Distribution among Cement Manufacturing Equipment [19,30,31].

Table 4
Percentage share of different types of fuel used in cement industries for few selected countries.

Types of fuel/Energy	% Share	Country	Reference
Electricity	11–14	Canada and India	[32,11]
Coal	33–41	Canada and India	[32,11]
Natural gas	7–64	Canada, Iran and India	[11,16,32]
Biomass	19	India	[11]
Petro-coke	13	Canada	[32]
HFO	4	Canada	[32]
Waste fuel	7	Canada	[32]
Fuel oil	36	Iran	[11,16,32]

1.1. Breakdown of energy use

Pyro-processing consumes major share of the thermal energy. About 33% of energy is used for operating materials and 38% for clinker (38%) crushing and grinding equipment. Another 22% of the energy is spent for pyro-processing [20,25,26]. Fig. 3 shows that grinding (finish and raw grinding) consumes major share (i.e. 60%) of total energy consumption in a cement manufacturing process. This can be targeted to reduce energy consumption with the application of economically viable energy efficient technologies. New technologies can be developed to reduce its energy consumption as sizeable energy is consumed in grinding operation of a cement manufacturing process. In another study [16], it was found that cement mill, raw mill, crusher and heater consume approximately 38%, 35%, 3% and 24% of total energy, respectively.

Table 4 shows electrical specific energy consumption at different sub-section of a cement industry. It has been observed that grinding and transportation consumed major share of energy followed by the kiln and cooler.

1.2. Conventional and alternative sources of energy used in cement industries

Cement kilns use different sources of energy to produce the high temperatures necessary for the clinker formation. Fuels are fed into the rotary Kiln and the energy generated as a result of combustion of fuel will evaporate any water from the raw materials and calcinations. Finally, the clinker is formed. The most common sources of fuel for the cement industry are: coal, fuel oil, petroleum coke, natural gas, diesel [16,18,20].

1.2.1. Classification of alternative fuels

Alternative fuels are one of the sources of energy used for many cement industries around the world. Alternative fuels are derived from the mixtures of industrial, municipal and hazardous wastes.

Table 5
Classification of alternative fuels used in cement industries.

Class	Types of fuel	Examples
Class 1	Gaseous alternative fuels	Refinery waste gas, landfill gas
Class 2	Liquid alternative fuels	Low chlorine spent solvents, hydraulic oils
Class 3	Pulverized, granulated or finely crushed solid alternative fuels	Sawdust, dried sewage sludge, granulated plastic, animal flours, fine crushed tyres
Class 4	Coarse-crushed solid alternative fuels	Crushed tyres, rubber/plastic waste, wood waste, re-agglomerated organic matter
Class 5	Lump alternative fuels	Whole tyres, plastic bales

These fuels are required to have an appropriate chemical content depending on the type of components and their organic contents. Alternative fuels used in cement industries can be solid or liquid, derived from municipal waste, industrial waste, or their mixtures [33]. Table 4 shows percentage share of energy used in cement industries. Table 5 shows the classification of alternative fuels [34].

There are four groups of solid alternative fuels that have been shown in Table 6 [34].

1.2.2. Desirable fuel properties

Alternative fuels are a mixture of various wastes and therefore these fuels must fulfill certain criteria. The chemical contents of the fuel must meet regulatory standards to ensure environmental protection. It must have the calorific value above certain level. The fuel should have a fairly homogeneous composition. The physical form must allow easy handling for transportation. It should be economically viable along with its availability [33]. The energy, ash, moisture and volatiles contents of the fuels should be given an important consideration. A flexible fuel feeding system need to be developed for alternative fuels to avoid problems associated with the feeding. The following properties are expected to be considered as alternative fuels [35]:

(1) Physical state of the fuel (solid, liquid, gaseous),
(2) Content of circulating elements (Na, K, Cl, S),
(3) Toxicity (organic compounds, heavy metals),
(4) Composition and content of ash,
(5) Content of volatiles,
(6) Calorific value—over 14.0 MJ/kg,
(7) Chlorine content—less than 0.2%,
(8) Sulfur content—less than 2.5%,
(9) PCB content—less than 50 ppm, heavy-metals content—less than 2500 ppm [out of which: mercury (Hg)—less than 10 ppm, and total cadmium (Cd), thallium (Tl) and mercury (Hg)—less than 100 ppm].
(10) Physical properties (scrap size, density, homogeneity),
(11) Grinding properties,
(12) Moisture content,
(13) Proportioning technology,
(14) The emissions released,
(15) The cement quality and its compatibility with the environment must not decrease,
(16) Alternative fuels must be economically viable.

Table 6
Group of solid alternative fuels.

Group	Types of groups	Dimensions	Humidity	Examples
Group 1	solid, dry fuels of relative fine size, which do not adhere	<2 mm	<10–15%	Wood dust, bark powder, rice husk
Group 2	solid, dry fuels of coarse size, which do not adhere	<20 mm	<10–15%	Plastic waste, wood chips, waste wood
Group 3	solid, dry fuels which tend to stick	<20 mm	<10–15%	Animal powder, impregnated wood dust
Group 4	mixtures of different lumpy fuels	<200 mm	<20%	Fluff, paper, cardboard

Table 7
Comparison of electrical and thermal SEC for few selected countries around the world [11].

Country	Electrical SEC (kWh/tonne)	Thermal SEC (GJ/tonne)
India	88	3.00
Spain	92	3.50
Germany	100	3.50
Japan	100	3.50
Korea	102	3.70
Brazil	110	3.70
Italy	112	3.80
China	118	4.00
Mexico	118	4.20
Canada	140	4.50
US	141	4.60
World best	65	2.72

Table 8
Specific thermal energy consumption in a clinker manufacturing process [21].

Kiln process	Thermal energy consumption (GJ/tonne clinker)
Wet process with internals	5.86–6.28
Long dry process with internals	4.60
1-stage cyclone pre-heater	4.18
2-stage cyclone pre-heater	3.77
4-stage cyclone pre-heater	3.55
4-stage cyclone pre-heater plus calciner	3.14
5-stage pre-heater plus calciner plus high efficiency cooler	3.01
6-stage pre-heater plus calciner plus high efficiency cooler	<2.93

1.3. Specific energy consumption

A plant or process with a lower SEC value corresponds to a similar plant or similar process that is more energy efficient. By comparing to SEC, the information developed can be used to assess the energy-efficiency potential of a plant. The SEC can also be used for evaluating and tracking a plant's progress in energy-efficiency improvements by eliminating the effects of a change in product mix [36].

Average specific thermal and electrical energy consumption is presented in Table 7 for few selected countries.

Table 8 shows specific thermal energy consumption for different types of clinker manufacturing process. It has been observed that pre-heating with different stages can reduce energy consumption significantly. Waste heat from different sources is used to pre-heat the clinker.

Table 9 shows specific electrical and thermal energy consumption for wet and dry process. It has been observed that dry process is more efficient compared to wet process. In a wet process extra energy is needed to remove moisture contained in wet slurry. Industries around the world are moving towards dry manufacturing process as they consume less energy than a wet process. Dry process consumes about 13% less energy (electrical) than a wet process. Dry process found to consume about 28% less fuel than a wet process.

Table 9
Specific electrical energy consumption in dry and wet process [16].

Process sections	Electrical energy consumption (kWh/tonne)	
	Dry	Wet
Raw material treatment and crushing	4	3
Mashing	44	10
Fans and coolers	23	25
Dust collector	6	8
Cement milling	45	45
Transportation	8	47
Total electricity required (kWh/tonne)	130	149
Fuel burned in furnaces (l/tonne)	112.5	156

Table 10
Specific energy consumption in Polish cement industry [37].

Year	Consumption of electric energy (kWh/tonne)	Consumption of unit gross heat energy (GJ/tonne)
2002	105	3.77
2003	105	3.48
2004	102	3.41
2005	101	3.46
2006	101	3.50
2007	95	3.64
2008	94	3.64

Table 10 shows specific electrical and thermal energy consumption trend in Polish cement industries. As industries are implementing different energy savings measures, this consequently will reduce specific energy consumption.

2. Machineries/equipment used in cement industries

Electrical motors, pumps, compressor, transformers, furnaces, fans, blowers, conveyors, ACs, chillers, cooling towers, Kiln, transportation, and lightings. These machines consume different forms of energy for cement manufacturing process. However, it was found in the literature that motor driven system (Motors, pumps, blowers, compressors, conveyors, fans) consume major share of total energy consumption in any industry around the world.

3. Cement manufacturing process [19,20,38,39]

Raw materials should be mixed precisely to manufacture Portland cement. The cement clinker requires appropriate amount of compositions of the elements calcium, silicon, aluminum and iron. All these raw materials together with the fuel ash must be combined to form the typical clinker composition as shown in Table 11 [38].

This is a dry cement manufacturing process, which operates with a nearly dry raw mix containing less than 20% moisture by mass. However, in a wet process water is added to the raw mix to form slurry and then is transported to the kiln.

Raw meals are grounded, blended, pre-calcined, and burned in manufacturing cement. In a cement manufacturing process, limestone and calcium, silicon, aluminum and iron oxides are crushed and then milled into a raw meal. This raw meal is blended in blending silos and is then heated in the pre-heating system. This will dissociate carbonate to calcium oxide and carbon dioxide. A secondary fuel is supplied to the preheating system so that temperature is sufficiently high. The meal then passed through the kiln for heating. Then a reaction takes place between calcium oxide and other elements. This reaction will produce calcium silicates and aluminates at about 1500 °C. Primary fuel is used to keep the temperature high enough in the burning zone for the chemical reactions to take place. A nodular product named clinker is produced and then allowed to leave the kiln. The clinker will be inter-ground with gypsum, limestone and/or ashes to a finer product called cement

Table 11
Composition of dry cement manufacturing process.

Elements	Composition (%)
CaO	65 ± 3
SiO_2	21 ± 2
Al_2O_3	5 ± 1.5
FeO_3	3 ± 1

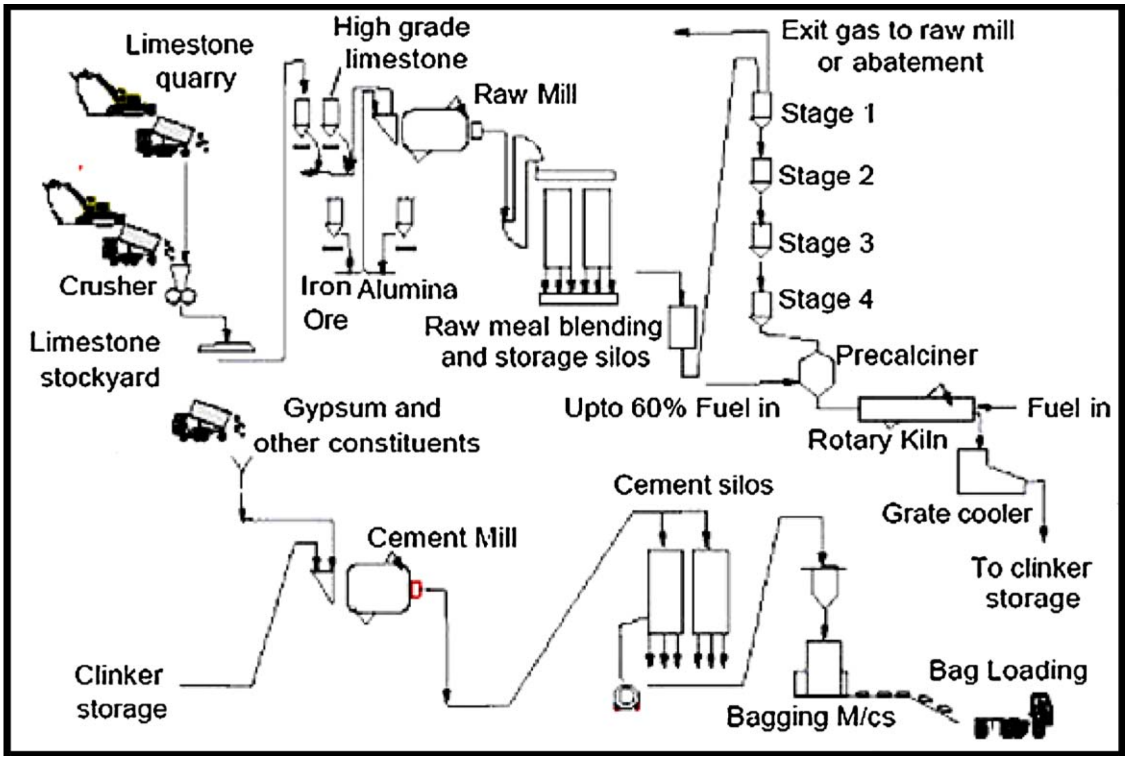

Fig. 4. Overview of cement manufacturing process [21].

[40–43]. A comprehensive cement manufacturing process can be found in the European cement Association [44]. Details of cement manufacturing process for few selected countries around the world can be found in [18,38,42,45,46].

However, Fig. 4 shows a comprehensive cement manufacturing process.

3.1. Brief description of cement manufacturing process

3.1.1. Limestone quarrying and crushing

Limestone supplies $CaCO_3$ for the cement production. Silica, alumina, and iron are considered to be other raw materials. The typical limestone used in cement production has 75–90% $CaCO_3$ in a raw feed. The reminder is magnesium carbonate ($MgCO_3$) and impurities. The lime and silica provide the main strength of the cement. Iron reduces the reaction temperature and gives the cement its characteristic grey color [47,48].

An open mining process is used for the quarrying operations. Quarrying is done through drilling, blasting and using heavy earth moving equipment such as bulldozers and dump trucks. Mechanical conveyor belts are then used to transport the quarried raw material.

The limestone size is reduced into 25 mm by feeding into a primary and secondary crusher. A further reduction in the inlet size can be made by passing through a tertiary crusher [21].

3.1.2. Additives storage hopper

It is necessary to add some iron, bauxite, quartzite and/or silica to achieve the required raw feed compositions. These materials can be stored in silos or hoppers and are transported using conveyor belts in conjunction with weigh-feeders. These additives prevent any natural deviation from the compositions of raw materials [47].

3.1.3. Raw mill

The raw mix need to be ground up before sending to the process stage. A ball mill or vertical roller mill (VRM) are used for a grinding process. The raw mix is dried using the part of the excess heat from the kiln in this stage. Impact with attrition principles are used for grinding the raw materials using a ball mill. Various sizes of balls are used inside the ball mills. A classifying liner is used to fix the position of different sizes of balls. The larger sized balls are used for impact grinding and the smaller balls for attrition grinding. A compression principle is used to grind the raw material in a VRM grinding process. The choice between a ball mill and VRM is governed by the moisture content of the raw material, the size of the plant, the abrasiveness of the material, the energy consumption levels, reliability, and economical viability [49].

3.1.4. Blending and storing silo

The variations in the composition of Kiln feed play an adverse impact on the efficiency of the kiln. To reduce the natural chemical variation in the various raw materials, it is necessary to blend and homogenize the raw material efficiently. Increasing the relative proportion of blending additives may reduce the amount of clinker used. This consequently will reduce the specific energy consumption of the final product. In order to blend and homogenize the raw materials properly, continuous blending silos are used [49].

3.1.5. Pre-heater and kiln

Clinkering is the main step in the dry cement manufacturing process. This is carried out in a pre-heater tower and in the Kiln. The pre-heater tower is comprised of a series of countercurrent flow cyclones. These cyclones transfer heat from the Kiln to the raw materials. The latest pre-heater towers contain a combustion chamber. This chamber is commonly known as pre-calciner. In this stage, the raw materials are calcined to produce CO_2. It may be reported that the kiln is the most important component of a cement

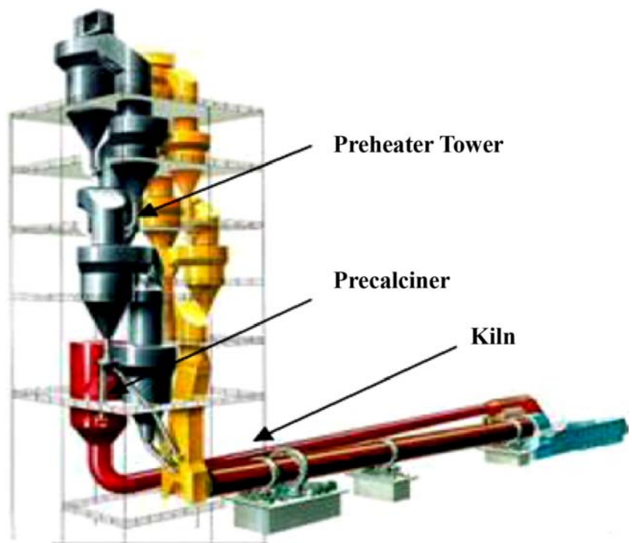

Fig. 5. Pre-heater Tower and Pre-calciner [38].

plant. It is 60–200 m long with diameters ranging from 3 to 9 m. Refractory bricks are used to cover its internal surfaces to prevent heat transfer. Fig. 5 shows pre-heater tower and pre-calciner.

Blended raw materials are fed into the upper end of the pre-heater tower and then passed through the end of the rotary Kiln. The Kiln is slowly rotated with about 1–2 RPM, and the raw material is tumbled through increasingly hotter zones. At this point, the sequence of chemical and physical changes will start to take place as the temperature is increased. The flame can be produced by powdered materials such as coal, petroleum coke, or by natural gas, oil, and recycled materials. A series of chemical reactions will take place and the raw material will be melted and fused together to form a clinker. The clinker is discharged as red-hot from the end of the kiln and passed through different types of coolers to partially recover the thermal energy and lower the clinker handling temperature.

3.1.6. Cooler

Temperature of the clinker coming out is approximately 1500 °C. Ambient air is blown using an air cooler over the hot clinker to reduce its temperature to approximately 170 °C [50].

3.1.7. Coal mill

The coal mill uses coal, coke or grinded pet coke with different size of balls. Larger sized balls are used for impact grinding and the smaller balls are used for attrition grinding.

3.1.8. Cement mill

This is the final step in a cement manufacturing process. In this step, the clinker is ground together with additives in a cement mill. It is a horizontal metallic cylinder containing metallic balls. A final product is formed with the crushing action of the balls and mixing the clinker with additives. Then the final output product cement is ground in a cement mill.

3.1.9. Cement storage silo

The cement storage silo is used for storing the finished cement.

4. Types of kiln

Kilns are used for the pre-processing stage of various types of cement. Every year billion tonnes of cement is manufactured and cement kilns are the heart of this production process [51,52].

Different types of kilns are briefly explained as below [53]:

a. Wet rotary kiln
b. Semi-wet rotary kiln
c. Semi-dry rotary kiln
d. Dry long rotary kiln
e. Dry rotary kiln with pre-heater
f. Dry rotary kiln with pre-heater and pre-calciner
g. Shaft kiln

Mainly vertical kilns (shaft kilns), and rotary kilns are used for the pyro-processing of the raw materials. China, India and in some other developing countries are using a number of vertical kilns. A rotary kiln looks like a tube with a diameter of up to 6 m. Its longitude is about 10–20 times its diameter for a short kiln and 32–35 times in case of long kilns. The kilns are installed with a slope of 3–4° with the horizontal. They rotate slowly to move the raw material towards the direction of the flame to the lower end of the kiln.

4.1. Wet rotary kiln

When water content of the raw material is within 15–25%, usually wet slurry is produced to feed into the kiln. The wet kiln feed contains about 38% of water. This will make the meal more homogeneous for the kiln, leading to less electrical energy use for the grinding. However, overall energy consumption will be higher to evaporate water in the slurry. This process is still in use in some countries. However, many countries are shifting from wet kiln to dry kiln to reduce the overall energy consumption.

4.2. Semi-wet rotary kiln

The wet raw material is processed in a filter after homogenizing to reduce moisture content. It is an improved version of the wet process. This is mainly used for retrofitting the existing wet kilns. This process can reduce energy consumption by 0.3 GJ/tonne of clinker.

4.3. Semi-dry rotary kiln

Waste heat recovered from the kiln is used to remove moisture content in this type of kiln. Then the dried meal is fed into the kiln. This will reduce overall energy consumption up to certain extent.

4.4. Dry long kiln

Long dry kilns without pre-heater and kilns with pre-heater are included in this group. It could be a shaft pre-heater or a one stage cyclone pre-heater. This technology still consumes more energy than new technologies because of the absence of the pre-heater in this type of kiln. Therefore, these technologies are not efficient like the new multi-cyclone type pre-heaters.

4.5. Dry kilns with pre-heater

This category includes kilns with 4–6 multistage cyclone pre-heaters. The raw materials are passed through the cyclones. Here each stage of cyclone has different range of temperatures. These cyclones are placed above each other in towers. A tower can be more than 100 m high. The energy use of kilns with suspension pre-heaters is much lower than the previous categories. As one part of the calcinations already takes place in the pre-heater, it is possible to reduce the energy consumption due to reduction in the length of the kiln. However, alkali may build-up which may cause extra energy use. The alkalis reduce the quality of the cement and can

Table 12
Kilns energy consumption [53,54].

Types of Kiln	Energy consumption (%)
1. Wet rotary kiln	1.8–3 to 3.6
2. Semi-wet rotary kiln	0.3
3. Semi-dry rotary kiln	–
4. Dry long rotary kiln	–
5. Dry rotary kiln with pre-heater	2.9–3.5
6. Dry rotary kiln with pre-heater and pre-calciner	8–11
7. Shaft kiln	3.7–6.6, average 4.8

Table 13
Average energy consumption of the dry and wet process [55,56].

Heat requirement	Dry process (GJ/tonne)	Wet process (GJ/tonne)
Chemical reactions	1.76	1.76
Evaporation of water	0	2.4
Heat lost	1.4	1.7
Total	3.2	5.8

block the operation of the preheated materials resulting in long interruptions in operation.

4.6. Dry kilns with pre-heater and pre-calciner

In this process, an additional combustion chamber is installed between the pre-heater and the kiln. This pre-calciner chamber consumes about 60% of the fuel used in the kiln, and 80–90% of the calcinations take place here. This reduces energy consumption by 8–11%. Low temperature waste heat from the combustion chamber can be recovered for other purposes. Consequently, this will reduce the NO_x emission because of the lower burning temperature. The capacity of the kilns could be increased up to 12,000 tonne/day by reducing length/diameter ratio to 10.

4.7. Shaft kiln

A number of shaft kilns can be found in China and India. In India their share is 10%, while in China it is over 80% of the capacities. Their usual size is between 20 and 200 tonnes/day, and many of them are operated manually.

Clinker quality is highly dependent on the homogenization of pellets and fuel, and on the air supply. Inadequate air supply or uneven air distribution makes combustion incomplete, resulting in low quality clinker and high CO and VOC emissions. We show the kilns energy consumption in Table 12 and average energy consumption of the dry and wet process in Table 13.

4.8. Some other kilns

There are other forms of Kilns whose important features are briefly presented in Table 14.

5. Energy savings measures

Cement manufacturing is an energy intensive process consuming about 12–15% of total energy consumption. Therefore opportunities exist to identify areas where energy savings measures can be applied so that energy can be saved along with the reduction of emission pollution. Table 15 presents list of energy savings measures for cement industries.

A few of the energy savings measures are briefly explained as below:

5.1. Optimization of grinding energy use [63]

- High efficiency separators (HES)
- Improved ball mill internals
- Vertical roller mills (VRM)
- High pressure grinding rolls (HPGR)
- Horizontal/ring roller mill

Grinding is a highly energy intensive process in the cement industry. Approximately 60–70% of the total electrical energy used in a cement plant is utilized for the grinding of raw materials, coal and clinker [63].

The electrical energy consumed in cement production is approximately 110 kWh/tonne. There is potential to optimize conventional cement clinker grinding circuits. The increasing demand for finer cement and the need for reduction in energy use and greenhouse gas emissions emphasize the necessity for grinding optimization. The current conventional closed grinding circuit can be increased by 10–20% by pre-crushing the clinker using the Barmac crusher. A stirred milling technology for fine cement grinding which is was found to be potential was discussed [30].

5.1.1. Improved grinding media

Improved wear resistant materials can be installed for grinding media, especially in ball mills. Grinding media are usually selected according to the wear characteristics of the material. Increases in the ball charge distribution and surface hardness of grinding media and wear resistant mill linings have shown a potential for reducing wear as well as energy consumption. Improved balls and liners made of high chromium steel is one such material. However other materials can also be considered. Improved liner design and grooved classifying liners can be considered as well. These may reduce grinding energy use by 5–10% in some mills. This

Table 14
Important features of various kilns [57–60].

	Rotary Kiln	Solar Kiln	Lime Kiln	Screw Kiln
Advantage	(a) Low rotational speed, 1–2 rpm (b) Calcinations zone temperature (700–900 °C) (c) Average daily production capacity 600 tonne clinker.	(a) Simple and insulated with natural air circulation. (b) Automatic dryers to improve thermal efficiency. (c) Solar kiln save energy.	(a) Safe operation kiln process and protect the environment. (b) Low cost and energy efficient (c) Can reduce heat energy consumption economically (d) Flue gas emission is reduced	(a) The temperature is low about 500 °C. (b) Simple and is controlling process in pyrolysis apparatus in screw kiln.
Disadvantage	(a) Cooling system is very sensitive. (b) Temperature is too high (1250 °C). (c) Energy consumption is very high.	(a) Solar kiln process and arrangement is complex.	(a) Controlling of the cooling system adjustment is very sensitive.	(a) This technology is mixed with other kiln system. (b) The screw kiln lower molecular weight gaseous products.

Table 15
Energy savings measures [61,62].

Raw Materials Preparation	
Efficient transport systems (dry process)	
Slurry blending and homogenization (wet process)	
Raw meal blending system (dry process)	
Conversion to closed circuit wash mill (wet process)	
High-efficiency classifiers (dry process)	
Fuel Preparation: Roller mills	
Clinker production (wet)	Clinker production (dry)
Energy management and process control	Energy management and process control
Seal replacement	Seal replacement
Kiln combustion system improvement	Kiln combustion system improvements
Kiln shell heat loss reduction	Kiln shell heat loss reduction
Use of waste heat	Use of waste heat
Conversion to modern grate cooler	Conversion to modern grate cooler
Refractoriness	Refractoriness
Optimize grate cooler	Heat recovery for power generation
Conversion to per-heater, pre-calciner kilns	Low pressure drop cyclones for suspension pre-heaters
Conversion to semi-dry kiln (slurry drier)	Optimize grate coolers
Conversion to semi-wet kiln	Addition of pre-calciner to per-heater kiln
Efficient kiln drives	Long dry kiln conversion to multi-stage per-heater kiln
Oxygen enrichment	Long dry kiln conversion to multi-stage per-heater, pre-calciner kiln.
	Efficient kiln drives
	Oxygen enrichment
Finish Grinding	
Energy management and process control	
Improved grinding media (ball mills)	
High-pressure roller press	
High efficiency classifiers	
General Measures	
Preventative maintenance (insulation, compressed air system, maintenance)	
High efficiency motors	
Efficient fans with variable speed drives	
Optimization of compressed air systems	
Efficient lighting	
Product & Feedstock Changes	
Blended cements	
Limestone cement	
Low alkali cement	
Use of steel slag in kin	
Reducing fineness of cement for selected uses	

will consequently reduce specific electrical energy consumption by 3–5 kWh/tonne cement [62].

5.1.2. Vertical roller mill (VRM)

The energy used for the actual grinding process depends mainly on the hardness of raw materials and the type of mill used (i.e. ball mill or vertical roller mill). Typically, an electrical motor of the ball mill uses about 14–15 kWh/tonne of raw mix. On the other hand, a VRM motor uses about 7–8 kWh/tonne. On an overall basis, a VRM consumes about 20% lower specific energy than a conventional closed circuit ball mill. A VRM is widely used for raw material and coal grinding in the cement industry.

5.1.3. High pressure roller grinding (HPGR)

A HPGR was first commercilized in 1985. Its success resulted in increasing number of applications in the cement industry [64]. Various circuit configurations were then developed for energy efficient cement grinding along with HPGR. Wustner [65] reported that 30% reduction in energy use was achieved after the conversion of closed circuit ball mill to a semi-finish grinding circuit with a HPGR. Applications of HPGR in different circuit alternatives have resulted in 10–50% energy savings compared to closed circuit ball milling operations [66]. A HPGR technology is gaining a wide acceptance within the mineral processing industry as it has a superior energy efficiency and a lower overall operating cost compared to alternative technologies that have been demonstrated at a number of operations throughout the world [67,68]. These grinding circuits have recently been developed. These are pregrinding, hybrid grinding, semi-finish grinding and finish grinding. The pregrinding system is applied if a production increase of 20–30% is required. Energy saving of 15–20% is achieved depending on material to be ground [63]. Aydogan et al. [69] reported that when the size reduction ratio changed from 308.2 to 4.4, the specific energy consumption of the HPGR was 8.02 and 4.05 kWh/tonne, respectively. Authors applied HPGR in different configurations and their corresponding specific and overall energy consumption is summarized in Table 16.

5.1.4. Horizontal/ring roller mill

The Horizontal/ring roller mill is a recently developed grinding process. The mill was developed by Horomill and Cemax Mill. Horomill is suitable for grinding raw meal, cement and minerals. However, Cemax Mill is mainly suitable for cement grinding. The mill can be used for pregrinding and finish grinding as well. This mill system has better reliability and energy savings over ball mill, roller mill and roller press. This type of mill consumes about 20% less energy than a ball mill [63].

Tables 17–21 show summary of energy savings, cost of installations, emission reductions and payback period for different energy savings measures

5.2. High efficiency classifier

A recent development in efficient grinding technologies is the use of high-efficiency classifiers or separators. Classifiers are used to separate the finely ground particles from the coarse particles. The large particles are then recycled back to the mill. This type of classifiers can be used in both the raw materials mill and in the finish grinding mill. Standard classifiers may have low separation efficiency. In this classifiers fine particles are recycled, resulting in extra energy consumption in the grinding mill. High efficiency classifiers reduce over-grinding by separating clean materials. High efficiency classifiers improve product quality along with energy savings [116–118].

Electrical energy savings of up to 8% can be achieved through the use of high-efficiency classifiers. About 15% increase in the grind-

Table 16
Specific energy consumption of HPGR circuit with different configurations [69].

Configurations	Overall circuit specific energy consumption (kWh/tonne)	HPGR circuit specific energy consumption (kWh/tonne)	Savings (%)
Open circuit HPGR–closed circuit ball mill grinding	34.19	4.05	12
Open circuit HPGR with partial recycling–closed circuit ball mill grinding	29.57	8.93	30
Hybrid grinding	29.85	–	
Closed circuit HPGR–closed circuit ball mill grinding	21.65	8.02	37
Semi-finish grinding	23.03	9.80	43

Table 17
Summary of energy savings in raw materials preparation.

Energy saving measure	Energy/Fuel saving	Electric saving	Cost	Emission reduction ($kgCO_2$/tonne)	Payback period (years)	Reference	Remarks
Efficient Transport Systems for Raw Materials Preparation (Dry Process)	2 kWh/tonne		Installation cost US$ 3/tonne			[70]	
	0.02 GJ/tonne		Retrofit capital cost US$ 3/tonne	0.53		[14]	
		3.4 kWh/tonne	Capital cost US$ 3/tonne	0.78	>10	[62]	Payback periods are calculated on the basis of energy savings alone
	1.24 kWh/tonne 2.35 kWh/tonne		0.39US$/tonne 0.52US$/tonne			[71]	
	0.03 GJ/tonne	2.54 kWh/tonne	Capital cost 2.7US$/tonne	0.41		[72]	
	0.035 GJ/tonne	3.13 kWh/tonne	0.47US$/tonne	3.22		[73]	
	0.03 GJ/tonne		Capital cost US$ 3/tonne	1.3		[62,74]	
Raw Meal Blending Systems (Dry Process)	1.0–2.5 kWh/tonne		Capital cost 3.7 US$/tonne			[70,75–78]	
	0.1 GJ/tonne	0.01 GJ/tonne	Retrofit capital cost 3.7US$/tonne	0.26		[14]	
	Reduction in SEC 1.4–4 kWh/tonne					[79]	SEC: specific energy consumption
		1.7–4.3 kWh/tonne		0.4–1.0		[62]	
	0.03 GJ/tonne	2.29 kWh/tonne	Capital cost 3.3US$/tonne		0.37	[62,72]	
	0.03 GJ/tonne	2.66 kWh/tonne	5.85US$/tonne	2.73		[73]	
	0.02 GJ/tonne	2.14 kWh/tonne	Capital cost 3.7US$/tonne	1.11		[62,74]	
Raw Meal Process Control for Vertical Mills (Dry process)	Reduction in SEC 0.8–1.0 kWh/tonne					[76]	SEC: specific energy consumption
	Reduction in SEC 6% kWh/tonne					[80]	SEC: specific energy consumption
		1.4–1.7 kWh/tonne		0.3–0.4	1	[62]	
	0.01 GJ/tonne	1.02 kWh/tonne	Capital cost 1.0US$/tonne	0.16		[73]	
	0.016 GJ/tonne	1.41 kWh/tonne	0.52US$/tonne	1.45		[62,74]	
	0.01 GJ/tonne	1.13 kWh/tonne	Capital cost 0.28 US$/tonne	0.59		[62,74]	
Use of Roller Mills (Dry Process)			Investment cost 5.5 US$/tonne			[70]	
	6–7 kWh/tonne					[76]	
	0.08 GJ/tonne	0.03 GJ/tonne	Capital cost 5.3 US$/tonne	1.85		[14]	
		10.2–11.9 kWh/tonne		2.3–2.7	>10	[62]	Payback periods are calculated on the basis of energy savings alone
	0.09 GJ/tonne	7.63 kWh/tonne	Capital cost 5US$/tonne	1.24		[62,74]	
	0.114 GJ/tonne	10.17 kWh/tonne	8.7US$/tonne	10.45		[73]	
	0.09 GJ/tonne	8.7 kWh/tonne	Capital cost 5.5US$/tonne	4.24		[62,74]	
High-efficiency Classifiers/Separators (Dry Process)	Reduction 2.8–3.7 kWh/tonne					[81,82]	
		8%	Investment cost 2.2US$/tonne			[70]	
	0.03 GJ/tonne	0.01 GJ/tonne	Retrofit capital cost 2US$/tonne	0.71		[14]	
			4.8–6.3 kWh/tonne	1.1–1.4	>10	[62]	Payback periods are calculated on the basis of energy savings alone
	0.04 GJ/tonne	3.18 kWh/tonne	Capital cost 2US$/tonne	0.51		[72]	
	0.057 GJ/tonne	5.08 kWh/tonne	3.5US$/tonne	5.23		[73]	
	0.05 GJ/tonne	4.08 kWh/tonne	Capital cost 2.2US$/tonne	2.12		[62,74]	
Slurry Blending and Homogenizing (Wet Process)	0.3–0.5 kWh/tonne					[76]	
		0.5–0.9 kWh/tonne		0.1–0.2	<3	[62]	
Wash Mills with Closed Circuit Classifier (Wet Process)		8.5–11.9 kWh/tonne		2.0–2.7	>10	[62]	Payback periods are calculated on the basis of energy savings alone
Roller Mills for Fuel Preparation	7–10 kWh/tonne					[76]	
		0.7–1.1 kWh/tonne		0.2–0.3		[62]	

Table 18
Summary of energy savings in clinker production.

Energy saving measure	Energy/Fuel saving	Electric saving	Cost	Emission reduction ($kgCO_2$/tonne)	Payback period (years)	References	Remarks
Improved Refractories for Clinker Making in All Kilns	0.12–0.4 GJ/tonne					[83]	
			Installation cost 0.25 US$/tonne				
	0.46–0.63 GJ/tonne					[84]	
	0.4–0.6 GJ/tonne			10.3–15.5		[62]	
Energy Management and Process Control Systems for Clinker Making in All Kilns	2.5–5% kWh/tonne		Investment cost 0.3 US$/tonne		2	[85]	
	0.1–0.2 GJ/tonne		Capital cost 0.3–1.7 US$/tonne	2.9–5.9	<2	[62]	
	0.1 GJ/tonne		Capital cost 1 US$/tonne	2.48		[72]	
	0.176 GJ/tonne	2.35 kWh/tonne	1.00 US$/tonne	16.61		[73]	
	0.16 GJ/tonne		Capital cost 1.00 US$/tonne	16.05		[62,74]	
Adjustable Speed Drive for Kiln Fan for Clinker Making in All Kilns		Reduced electricity use by 5.5 kWh/tonne				[86]	
		Reduction in electricity consumption 40%				[87]	
	30%					[84]	
	0.62 kWh/tonne		Cost saving 0.073US$/tonne			[71]	
		6.1 kWh/tonne	Capital cost 0.23US$/tonne	1.4	2–3	[62]	
	0.068 GJ/tonne	6.1 kWh/tonne	0.23US$/tonne	6.27		[73]	
	0.05 GJ/tonne	4.95 kWh/tonne	Capital cost 0.23US$/tonne	2.57		[62,74]	
Installation or Upgrading of a Preheater to a Preheater/Precalciner Kiln for Clinker Making in Rotary Kilns	0.4 GJ/tonne					[88]	
	Reduction in SFC 0.16–0.7 GJ/tonne					[89]	SFC: specific fuel consumption
	Reduction in SFC 3.4 GJ/tonne						SFC: specific fuel consumption
	0.16–0.7 GJ/tonne		Capital cost 9.4–28US$/tonne	4.1–18.1	5	[62]	
	0.43 GJ/tonne		18.3US$/tonne	40.68		[73]	
	0.35 GJ/tonne		Capital cost 18US$/tonne	34.59		[62,74]	
Conversion of Long Dry Kilns to Preheater/Precalciner Kilns for Clinker Making in Rotary Kilns	1.4 GJ/tonne					[70]	
	0.4 GJ/tonne		Retrofit capital cost 10.0 US$/tonne	20.46		[14]	
	1.4 GJ/tonne		Capital cost 8.6–29 US$/tonne	36	>10	[14]	
	1.14 GJ/tonne		Capital cost 20 US$/tonne	112.61		[62,74]	
Dry Process Upgrade to Multi-Stage Preheater Kiln for Clinker Making in Rotary Kilns	0.9 kWh/tonne		Specific cost 39–41 US$/annual tonne			[70]	
	Reduction in SFC 4.1–3.6 GJ/tonne					[90]	SFC: specific fuel consumption
	0.9 GJ/tonne					[70]	
	0.9 GJ/tonne		Retrofit capital cost 20.0US$/tonne	46.05		[14]	
	0.9 GJ/tonne		Capital cost 28–41 US$/tonne	23	>10	[62]	
	0.73 GJ/tonne		Capital cost 35.00 US$/tonne	72.39		[62,74]	
Increasing Number of Preheater Stages in Rotary Kilns	0.111 GJ/tonne		Capital cost 2.78 US$/tonne			[71]	
	0.098 GJ/tonne		2.58 US$/tonne	9.3		[73]	
	0.09 GJ/tonne Fuel, 0.08 GJ/tonne Energy		Capital cost 2.54 US$/tonne	8.44		[71,74]	
Conversion to Reciprocating Grate Cooler for Clinker Making in Rotary Kilns	>8%					[91]	
	Reduction in SFC 3% GJ/tonne					[92]	SFC: specific fuel consumption
	0.3 GJ/tonne		Retrofit capital cost 0.5 US$/tonne	16.37		[14]	
	0.27 GJ/tonne		Capital cost 0.4–5.5 US$/tonne	6.3	1–2	[62]	
	0.22 GJ/tonne Fuel, 0.19 GJ/tonne Energy		Capital cost 2.8 US$/tonne	20.46		[62,74]	
Kiln Combustion System Improvements for Clinker Making in Rotary Kilns	2–10%					[93]	
	>10%					[83]	
	5–10%					[94]	
	2.7–5.7%					[95]	
	0.2 GJ/tonne Fuel, 0.17 GJ/tonne Energy		Retrofit capital cost 0.98 US$/tonne	8.8		[14]	
	0.1–0.5 GJ/tonne		Capital cost 1.0 US$/tonne	2.6–12.9	2–3	[62]	
	0.24 GJ/tonne		Capital cost 1.0 US$/tonne	24.13		[62,74]	
Indirect Firing for Clinker Making in Rotary Kilns	0.015–0.022 GJ/tonne		Capital cost 7.4 US$/tonne	0.39–0.57		[62]	

Table 18 (*Continued*)

Energy saving measure	Energy/Fuel saving	Electric saving	Cost	Emission reduction ($kgCO_2$/tonne)	Payback period (years)	References	Remarks
Optimize Heat Recovery/Upgrade Clinker Cooler for Clinker Making in Rotary Kilns	0.05–0.08 GJ/tonne					[96]	
	0.16 kWh/tonne					[70]	
	0.08 GJ/tonne					[97]	
	0.1 GJ/tonne		Retrofit capital cost 0.2 US$/tonne	5.12		[14]	
	0.062 GJ/tonne		Investment cost 0.11–0.33 US$/annual tonne			[71]	
	0.05–0.16 GJ/tonne		Capital cost 0.1–0.3 US$/tonne	0.8–3.7	1–2	[62]	
	0.07 GJ/tonne		Capital cost 0.2 US$/tonne	1.59		[72]	
	0.11 GJ/tonneFuel, 0.088 GJ/tonne Energy		18.3 US$/tonne	40.68		[73]	
	0.09 GJ/tonne Fuel 0.07 GJ/tonne Energy		Capital cost 0.2 US$/tonne	8.01		[62,74]	
Low Temperature Heat Recovery for Power Generation1 for Clinker Making in Rotary Kilns		20–35 kWh/tonne	Capital cost 800–1250 US$/kW	4.6–8.1	<3	[62]	Domestic technology cost is 890.41–1484 US$ per investment, which is about 1484 US$ less than foreign technology (2374.43–3264.84 US$/kW).
	0.345 GJ/tonne	30.8 kWh/tonne	1357.7 US$/kW	31.66		[73]	
	0.25 GJ/tonne	24.73 kWh/tonne	Capital cost 1828US$/kW	12.83		[71,74]	
Seal Replacement for Clinker Making in Rotary Kilns	Reduction in SFC 4%					[98]	SFC: specific fuel consumption
	0.011 GJ/tonne			0.3	≤0.5	[62]	
High Temperature Heat Recovery for Power Generation for Clinker Making in Rotary Kilns	0.22 GJ/tonne	0.07 GJ/tonne	Retrofit capital cost 1.8 US$/tonne	3.68		[14]	
		22 kWh/tonne	Capital cost 2.2–4.4 US$/tonne	5.1	3	[14]	
	0.21 GJ/tonne	17.84 kWh/tonne	Capital cost 3.3 US$/tonne	9.25		[62,74]	
Low Pressure Drop Cyclones for Suspension Preheaters for Clinker Making in Rotary Kilns	0.66–1.1 kWh/tonne					[96]	
	4.4 kWh/tonne					[86]	
	0.04 GJ/tonne	0.01 GJ/tonne	Retrofit capital cost 3.1 US$/tonne	0.74		[14]	
		0.7–4.4 kWh/tonne	Capital cost 3 US$/tonne	0.16–1.0	>10	[62]	
	0.04 GJ/tonne	3.28 kWh/tonne	Capital cost 2.7 US$/tonne	0.53		[72]	
	0.029 GJ/tonne	2.6 kWh/tonne	3.05 US$/tonne	2.67		[73]	
	0.02 GJ/tonne	2.11 kWh/tonne	Capital cost 3.00 US$/tonne	1.09		[62,74]	
Efficient Kiln Drives for Clinker Making in Rotary Kilns	0.55 kWh/tonne		Capital cost + 6%			[99]	
		0.55–3.9 kWh/tonne	Capital cost + 0–6% US$/tonne	0.13–0.9		[62]	Initial costs given as the additional % required relative to standard U.S. technology (0–6%).
	0.006 GJ/tonne	0.55 kWh/tonne	0.22 US$/tonne	0.57		[73]	
	0.005 GJ/tonne	0.45 kWh/tonne	Capital cost 0.19 US$/tonne	0.23		[62,74]	
Replacing Vertical Shaft Kilns with New Suspension Preheater/Precalciner Kilns for Clinker Making in Vertical Shaft Kilns	2.4 GJ/tonne					[100]	
	2.4 GJ/tonne		Capital cost 28–41 US$/tonne	62	5–7	[62]	Payback period calculated using approximate costs of bituminous coal for industrial boilers (bitu2) in China for the year 2005 (approximately US$ 55/tonne coal).

Table 19
Summary of energy savings in finish grinding.

Energy saving measure	Energy/Fuel saving	Electric saving	Cost	Emission reduction ($kgCO_2$/tonne)	Payback period (years)	Reference	Remarks
Process Control and Management in Grinding Mills for Finish Grinding	3–3.5 kWh/tonne				6 months–2 years	[80,101]	
	Reduction in EC 2%					[102]	
	3%					[103]	
	2.5–10%					[104]	
		3.8–4.2 kWh/tonne		0.9–1.0	<1–2	[62]	
	0.045 GJ/tonne	4 kWh/tonne	0.47 US$/tonne	4.11		[73]	
	0.04 GJ/tonne	3.24 kWh/tonne	Capital cost 0.5 US$/tonne	1.68		[62,74]	
Vertical Roller Mill for Finish Grinding	16.9 kWh/tonne					[105]	
	10 kWh/tonne					[71,106]	
	0.29 GJ/tonne	25.93 kWh/tonne	7.95 US$/tonne	26.66		[73]	
	0.2 GJ/tonne	17 kWh/tonne	Capital cost 5 US$/tonne	8.82		[62,74]	
High Pressure (Hydraulic) Roller Press for Finish Grinding	30%		cost saving 500,000 US$/tonne			[107]	
	0.09 GJ/tonne	0.03 GJ/tonne	Retrofit capital cost 2.5 US$/tonne	1.28		[14]	
	7–15%					[108]	
		8–28 kWh/tonne		1.8–6.3	>10	[62]	Payback periods are calculated on the basis of energy savings alone
	0.31 GJ/tonne	25.00 kWh/tonne	Capital cost 4.00 US$/tonne	4.05		[72]	
	0.273 GJ/tonne	24.41 kWh/tonne	7.95 US$/tonne	25.09		[73]	
	0.18 GJ/tonne	16 kWh/tonne	Capital cost 5.00 US$/tonne	8.3		[62,74]	
Horizontal Roller Mill for Finish Grinding	35–40%					[108]	
	0.3 GJ/tonne	0.1 GJ/tonne	Capital cost 4.00 US$/tonne	4.33		[14]	
High Efficiency Classifiers for Finish Grinding		Reduction in electricity use 6–7 kWh/tonne				[70,109]	
		Reduction in electricity use 1.9–2.5 kWh/tonne				[81]	
		0–7 kWh/tonne				[103]	
	0.3 GJ/tonne	0.01 GJ/tonne	Retrofit capital cost 2.5 US$/tonne	0.48		[14]	
	1.62 kWh/tonne		0.19 US$/tonne	0.48		[71]	
		1.9–6 kWh/tonne		0.4–1.4	>10	[62]	Payback periods are calculated on the basis of energy savings alone
	0.05 GJ/tonne	4 kWh/tonne	Capital cost 2.0 US$/tonne	2.07		[62,74]	
Improved grinding media	3–5 kWh/tonne					[93]	
	0.02 GJ/tonne	0.1 GJ/tonne	Retrofit capital cost 0.7 US$/tonne	0.32		[14]	
		3–5 kWh/tonne		0.7–1.2	8	[62]	Payback periods are calculated on the basis of energy savings alone
	0.02 GJ/tonne	1.8 kWh/tonne	Capital cost 0.7 US$/tonne	0.29		[72]	
	0.068 GJ/tonne	6.1 kWh/tonne	1.11 US$/tonne	6.27		[73]	
	0.05 GJ/tonne	4 kWh/tonne	Capital cost 0.7 US$/tonne	2.07		[62,74]	

Table 20
Summary of energy savings in general measures.

Energy saving measure	Energy/Fuel saving	Electric saving	Cost	Emission reduction ($kgCO_2$/tonne)	Payback period (years)	Reference	Remarks
High-Efficiency Motors and Drives	3–8%					[86,91]	
	0.06 GJ/tonne	0.02 GJ/tonne	Retrofit capital cost 0.2US$/tonne	0.93		[14]	
		0–6 kWh/tonne		0–1.3	<1	[62]	
	0.31 GJ/tonne	25 kWh/tonne	Capital cost 4US$/tonne	4.05		[72]	
	0.051 GJ/tonne	4.58 kWh/tonne	0.34US$/tonne	4.7		[73]	
	0.03 GJ/tonne	3 kWh/tonne	Capital cost 0.22US$/tonne	1.56		[62,74]	
Adjustable or Variable Speed Drives	0.08–0.17 kWh/tonne 0.11–0.21 kWh/tonne 0.41 kWh/tonne		Cost saving: 0.013 –0.014US$/tonne 0.026–0.032US$/tonne 0.026–0.029US$/tonne			[71]	
	0.1 GJ/tonne	0.03 GJ/tonne	Retrofit capital cost 0.95US$/tonne	1.68		[14]	
		6–8 kWh/tonne		1–2	2–3	[62]	
	0.09 GJ/tonne	7 kWh/tonne	Capital cost 1.00US$/tonne	1.13		[72]	
	0.102 GJ/tonne	9.15 kWh/tonne	1.43US$/tonne	9.41		[73]	
High-Efficiency Fans	0.13 kWh/tonne 0.11 kWh/tonne 0.65 kWh/tonne 0.134 kWh/tonne 0.7 kWh/tonne 0.36 kWh/tonne		Cost saving: 0.01US$/tonne 0.006US$/tonne 0.077US$/tonne 0.107US$/tonne 0.073US$/tonne 0.036US$/tonne			[71]	
Reduce Leaks in Compressed Air Systems	20% Reduction of annual EC					[110]	EC: energy consumption
Reducing the Inlet Air Temperature in Compressed Air Systems	1%				2–5	[94]	
Compressor Controls in Compressed Air Systems	12% annually 8% per year 3.5%					[94,110,111]	
Sizing Pipe Diameter Correctly in Compressed Air Systems	20% Reduction of annual EC					[110]	EC: energy consumption
Heat Recovery for Water Preheating in Air Compressor Systems	20%				<1	[110]	
Lighting Control for Plant Wide Lighting	10–20%				<2	[112]	
Replace Mercury Lights by Metal Halide or High Pressure Sodium Lights for Plant Wide Lighting	50–60%					[113]	
Replace Magnetic Ballasts with Electronic Ballasts for Plantwide Lighting	12–25%					[114]	

Table 21
Summary of energy savings in product and feedstock changes.

Energy saving measure	Energy/Fuel saving	Electric saving	Cost	Emission reduction ($kgCO_2$/tonne)	Payback period (years)	Reference	Remarks
Changing Product and Feedstock: Blended Cements	9–23 MJ/tonne			0.3–7.1		[75]	
	1.53 GJ/tonne Fuel, 1.36 GJ/tonne Energy		Retrofit capital cost 0.7 US$/tonne			[14]	
	2.6–3.4 GJ/tonne					[84]	
	10%			76.31		[84]	
	0.9–3.4 GJ/tonne Fuel		Capital cost 0.7 US$/tonne	21–85	<1	[62]	Data from Chinese case studies indicate saving of 2.6–3.4 GJ/tonne clinkers, while U.S. data shows saving of 0.9 GJ/tonne clinker.
	1.28 GJ/tonne		Capital cost 0.65 US$/tonne	31.08		[72]	
	1.77 GJ/tonne Fuel, 1.68 GJ/tonne Energy		0.73 US$/tonne	160.02		[73]	
	2.19 GJ/tonne Fuel 2.09 GJ/tonne Energy		Capital cost 0.72 US$/tonne	212.54		[62,74]	
Changing Product and Feedstock: Use of Waste-Derived Fuels	0.6 GJ/tonne		Installation cost 0.11–1.1 US$/annual tonne			[94]	
	1.53 GJ/tonne Fuel, 1.36 GJ/tonne Energy		Capital cost 0.7 US$/tonne	76.31		[14]	
	>0.6 GJ/tonne		Capital cost 0.1–3.7 US$/tonne	12	1	[62]	For calculating specific CO_2 savings for this measure, an emission factor for solvents of 0.02 tonneC/GJ
	0.49 GJ/tonne		Capital cost 1.1 US$/tonne	48.26		[62,74]	
Changing Product and Feedstock: Limestone Portland Cement	Reduction in FC 5% Reduction in PC 3.3 kWh/tonne		Reduction in operation cost 5%	5%		[115]	FC: Fuel consumption. PC: Power consumption
	0.3 GJ/tonne	2.8 kWh/tonne		8.4	<1	[62]	
	0.23 GJ/tonne Fuel, 0.26 GJ/tonneEnergy	3.3 kWh/tonne	0.12 US$/tonne	25.1		[73]	
	0.28 GJ/tonne Fuel, 0.32 GJ/tonneEnergy	3.3 kWh/tonne	Capital cost 0.18 US$/tonne	29.86		[62,74]	
Changing Product and Feedstock: Low-Alkali Cement	8–21 MJ/tonne					[75]	
	0.19–0.5 GJ/tonne			4.6–12.1	Immediate	[62]	
Changing Product and Feedstock: Use of Steel Slag in Kiln	0.19 GJ/tonne			4.9	<2	[62]	
	0.15 GJ/tonne		Capital cost 0.4 US$/tonne	15.28		[62,74]	

Table 22
Optimization results for different cogeneration systems [17].

	Single flash	Daul-pressure	ORC	Kalina
Net power output (kWh)	103,200	99,828	89,319	109,575
Exergy efficiency (%)	42.3	40.9	36.6	44.9

ing mill capacity can be made by replacing a conventional classifier with high-efficiency one. The product quality can be improved further due to a more uniform particle size, both in raw meal and cement. This may result in fuel savings in the kiln and improved clinker quality [14,62,119,120].

5.3. Waste heat recovery

Waste heat recovery from the hot gases in the system can be considered as a potential option to improve energy efficiency in industrial processes [52]. Chen et al. [121] examined the performance of the CO_2 trans-critical power cycle utilizing low-grade waste heat compared to an organic Rankine cycle using R123 as a working fluid. Authors found that the carbon dioxide trans-critical power cycle had a slightly higher power output than that of the ORC under the same conditions. Legmann [122] used ORC supplied to the cement industry to recover the heat available from clinker cooler and generate electricity on a continuous basis without interfering with the cement production process. In order to recover waste heat from the pre-heater exhaust and clinker cooler exhaust gases in cement plant, a single flash steam cycle, dual-pressure steam cycle, ORC and the Kalina cycle are used for cogeneration in cement plants. The optimum performances for different cogeneration systems are compared under the same conditions by [17] and results are presented in Table 22.

Khurana et al. [26] performed an energy balance of a cogeneration system for a cement plant in Indiana. Authors found that about 35% of the input energy was lost with the waste heat streams. A steam cycle was selected to recover the heat from the streams using a waste heat recovery steam generator and it was estimated that about 4.4 MW of electricity could be generated.

Sogut et al. [46] examined heat recovery from rotary kiln for a cement plant in Turkey. It was determined that 5% of the waste heat can be utilized with the heat recovery exchanger. The useful heat obtained is expected to partially satisfy the thermal loads of 678 dwellings in the vicinity through a new district heating system. This system is expected to decrease domestic-coal and natural gas consumption by 51.55% and 62.62% respectively.

The waste heat can be recovered as steam at the high pressure boiler (HPB) to replace the gas conditioning tower. The steam generated can drive the steam turbine to generate electricity at the required output [123].

5.4. The use of waste heat recovery steam generator (WHRSG)

There are opportunities exist within the plant to capture the waste to generate electricity. The most accessible and the most cost effective waste heat losses available are the clinker cooler discharge and the kiln exhaust gas. The exhaust gas from the kilns is, on average, 315 °C, and the temperature of the air discharged from the cooler stack is 215 °C. Both streams can be directed through a waste heat recovery steam generator (WHRSG). The available energy is then transferred to water through the WHRSG. The available waste energy is used to generate steam. This steam would then be used to power a steam turbine driven electrical generator. The electricity generated would offset a portion of the purchased electricity, thereby reducing the electrical demand.

In order to determine the size of the generator, the available energy from the gas streams must be estimated. Once this is determined, an approximation of the steaming rate for a specified pressure can be found. The steaming rate and pressure will determine the size of the generator.

Because of various losses and inefficiencies inherent in the transfer of energy from the gas stream to the water circulating within the WHRSG, all of the available energy may not be transferred. Therefore, a reasonable estimate on the efficiency of the WHSRG must be made.

5.5. Use of waste heat to pre-heat the raw material

One of the most effective methods of recovering waste heat in cement plants would be to preheat the raw material before the clinkering process. Directing gas streams into the raw material just before the grinding mill generally does this. This would lead to a more efficient grinding of the raw material in addition to increasing its temperature. However, in most plants, the fresh raw material taken from the mill is not directly sent to the kiln. Therefore, the temperature increase of the raw material does not generally make sense because it will be stored in silos for a while before entering the clinkering process.

5.6. Heat recovery from kiln surface

A waste heat loss by convection and radiation through the hot kiln surfaces has been found to be about 15.11% of the input energy. This heat loss can be reduced using a secondary shell on the kiln surface. Heat loss can be protected by insulating the external surface of the cyclones and ducts in the pre-heater unit. This will consequently reduce fuel consumption by 2% with highly viable payback times ranging from 0.07 to 0.72 yr [124,125].

5.7. Cement plant heat source conditions for power generation

The suspension pre-heater (SP) exhaust gas and the hot air from the clinker cooler discharge are the sources of waste heat. These heat sources may be used separately or in combination for WHR power generation. These two heat sources have different temperature levels and include suspended dust particles of different volumetric loading levels and particle fireside characteristics. The SP exhaust gas is used within the cement plant for drying raw materials. The WHR generation system design must consider the drying requirements in the cement plant raw mill to optimize the amount of electricity generated on an annual basis [125].

6. Conclusions

Following conclusions can be drawn from this study:

1. It has been found that cement manufacturing is an energy intensive process consuming about 12–15% of total energy consumption of a country.
2. Pyro-processing found to be consuming major share of the total energy (i.e. 93–99% in some cases) use.
3. Among the different sections, grinding consumes about 60% of total energy consumption in a cement industry. Significant

amount of heat is wasted in grinding. Therefore, improvements can be made in this section to reduce heat loss or recycle heat.

4. It was also observed that coal is the major source of energy for few selected countries. Therefore, fuel substitution can be considered as an alternative option to reduce environmental pollution.
5. Use of alternative fuels or waste heat recovery could be a good solution. However, challenges associated with the use of alternative fuels must be overcome. This could be a potential area for future research and development.
6. A dry process found to be more energy efficient compared to wet process and industries are moving towards dry process to reduce energy consumption in the cement industries. Further reduction in energy consumption can be made possible with the introduction of various stages in a dry process.
7. A wet process which is energy in-efficient and still available in some countries should be replaced or upgraded to reduce its overall energy consumption.
8. It has been identified that sizeable amount of energy can be saved and emission can be reduced in raw materials preparation, clinker production, finish grinding, general areas, products and feedstock changes applying different energy savings measures.
9. Among the various energy savings measures listed in Table, VRM, high pressure grinding rolls or horizontal/ring roller mill can be considered viable options due to the simplicity of the systems along with low specific energy consumption.
10. It was found that raw meal process control for vertical mills in dry process can reduce SEC by 6% with a payback period of about 1 year.
11. Use of an adjustable speed drive for kiln fan for clinker making found to be saved about 30% of energy consumption with a payback period of about 2–3 years. Upgrading a pre-heater in clinker is also found to be saved energy consumption by 11–14%.
12. Conversion to reciprocating grate cooler for clinker making in rotary kilns may save more than 8% of energy consumption in clinker production with a payback period of 1–2 years. Kiln combustion system improvements for clinker making in rotary kilns found to save about 2–10% of energy consumption in this section.
13. Horizontal roller mill for finish grinding found to save highest amount of energy of about 35–40% of total consumption in the grinding section.
14. Replacing mercury lights by metal halide or high pressure sodium lights for a plant wide lighting will save about 50–60% of the total lighting energy consumption.
15. It has been observed that there are many economically viable technologies available to reduce energy use and emissions associated with the burning fuel to produce electrical energy. However, international, regional and local experiences indicate that due to lack of technical knowledge of the staff about the energy-efficiency measure, lack of government policies, plant-specific operational conditions, investors' preferences, and high initial capital costs despite the fact that the payback period of the technology is short, these available technologies are not fully utilized. Therefore, awareness campaign through mass media, information dissemination through different innovative approach should be devised for effective energy efficiency practices for an industrial facility.

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